POWERING YOUR EVERY STEP: HARNESSING ENERGY BY TRIBOELECTRIC NANOGENERATORS AND SHOES

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Abstract— In 2023, there were 745 million people without access to electricity, largely due to a lack of affordability and supply chain disruptions. A possible solution to this issue, triboelectric nanogenerators (TENG), work by harvesting mechanical energy and converting it into usable electrical energy. Because of this ability, TENGs can alleviate this energy crisis by harnessing sustainable energy through human movement. A specific example of TENGs being incorporated into textiles that we will examine is TENG-implanted shoes. Since TENGs convert energy into a usable state rather than creating energy, as is the case with burning fossil fuels, they are sustainable in and of themselves with their fuel being a renewable resource. This paper will then evaluate the feasibility of TENG being used in real-world applications and compare its technology to traditional-on-the-market generators. Lastly, the paper will conclude with the sustainability of TENG specifically, comparing the use of biodegradable materials versus nonrenewable materials.

Key Words— Electrical energy, Mechanical energy, Textiles, Triboelectric effect, Triboelectric nanogenerators

TRIBOELECTRIC NANOGENERATORS CHANGE ENERGY HARVESTING TECHNOLOGIES: AN OVERVIEW

As the world continues to develop, the need for energy increases across all sectors, but despite this, access to energy around the world is not able to match the speed. According to World Energy and Climate Statistics, since the 1990's the need for electric energy has increased exponentially, with the global energy consumption growth in 2022 being 2.1% [1]. But just as the need for energy is increasing, technological innovation is increasing right alongside it. One such technological innovation is triboelectric nanogenerators. TENGs, as detailed by Shen et al., are compact energy harvesters that are able to collect energy from mechanical movements and can act as a power source for a device [2]. TENGs are utilized in many applications, more specifically in the textile industry where they are being incorporated to harvest energy from human movements. These textiles are versatile and are therefore able to be used in more applications. One example of TENGs being used within textiles is in shoe insoles, allowing them to harvest power from mechanical energy. As Tang stated in "Self-Powered Versatile Shoes Based on Hybrid Nanogenerators shoes", a mini nanogenerator would be embedded into a shoe insole and would then serve as an energy cell that can be used for a multitude of things from powering a GPS to charging a cellphone [3].

TENGs are energy harvesters that can serve as a clean energy alternative to batteries, as batteries need regular replacement and recharging. Batteries also contain toxic and expensive substances, making their disposal can be difficult and wasteful. According to "Triboelectric Nanogenerator: Structure, Mechanism, and Applications", Energy harvesters are a good alternative to using other sources of energy because they do not require frequent replacement. So long as the mechanical energy, such as energy from human movement, remains, the energy harvester can extract electrical energy perpetually [4].

TENG uses triboelectrification, the principle when two materials meet and separate a difference of charge is created on each material. According to author Kim in "Triboelectric Nanogenerator: Structure, Mechanism, and Applications", TENG takes the difference of charge created by the movement of the two surfaces and transforms it into usable electrical energy [4]. This means that TENGs can provide power to devices in real time without having to store energy in a battery.

TENG offers sustainable energy harvesting, particularly in small-scale applications like shoe insoles and wearable electronics [5]. From the research paper "Electromagnetic Generator," compared to traditional generators and electromagnetic generators, TENG excels in flexibility, high power output in small devices, and can be made from renewable sources. They are lightweight, flexible, and can harvest energy from mechanical motion waves found in nature [6]. However, as the research paper, "Small-sized, lightweight, and flexible triboelectric nanogenerator enhanced by PTFE/PDMS nanocomposite electret," unlike traditional generators and batteries, TENG lacks high power output in larger scale applications [7].

From a sustainable standpoint, TENG devices are primarily made from non-renewable materials, however, recent advances allow for such devices to be made of biodegradable materials. These natural materials from the article, "Environmentally Friendly Natural Materials for Triboelectric Nanogenerators: A Review," by L. Liu, et al, explains that natural materials can be implemented into TENG devices without changing the voltage power in small-scale applications significantly. However, the materials used in TENG devices now are made from non-renewable materials such as aluminum, and copper [8]. The mining of these precious metals poses a great danger to the environment and the public. From the National Institute of Health's article, "Potential Health Impacts of Bauxite Mining in Kuantan," the mining of aluminum can cause toxic waste to pollute the air and increase health problems [9]. When mining copper, there are similar risks, specifically with damaging water quality as the article by R. Garwin, "How Sulfide-Ore Copper Mines Pollute," writes [10]. TENG device materials can be sustainability sourced but are still being made from precious metal materials. The switch from these types of materials determines the positive or negative effect TENG has on the environment.

TENG: HARNESSING ENERGY FROM MOVEMENT

The Triboelectric Effect

TENG uses the triboelectric effect or triboelectrification to convert mechanical energy into electrical energy [4]. Triboelectrification is the concept when two materials come into contact with one another through mechanical energy, and an electric charge moves from one to the other. This creates an electrostatic charge on each surface. Then, when the materials are separated by mechanical energy again, the charges do not transfer back as quickly, leaving one material with excess charge, and another with a deficient charge [4].

In order to take full advantage of the triboelectric effect, the right materials are integral to creating the largest difference in charge. As discussed by Renyun Zhang and Håkan Olin from the Department of Natural Sciences at Mid Sweden University, in theory, two materials with the highest differences in charge affinity would be ideal for generating the highest energy output possible [11]. Two materials with the largest differences in charge affinity are not always chosen for triboelectric nanogenerators, however, because there are other physical properties that contribute to triboelectrification such as friction and elasticity [4].

Using the Triboelectric Effect to Our Advantage

As stated in "Material aspects of triboelectric energy generation and sensors," TENGs are typically described in the context of the four layers: the charge-generating layer, the charge-trapping layer, the charge-collecting layer, and the charge-storage layer [12]. As explained by Zimeng Ma, Xia Cao, and Ning Wang in "Biophysical Sensors Based on Triboelectric Nanogenerators," the charge-generating layer of TENG-based systems works in one of four modes, including vertical contact separation, lateral sliding, freestanding triboelectric layer, and single electrode modes [13]. Figure 1 shows the basic concept of the four different TENG modes and the motion in which each method moves the dielectric materials.

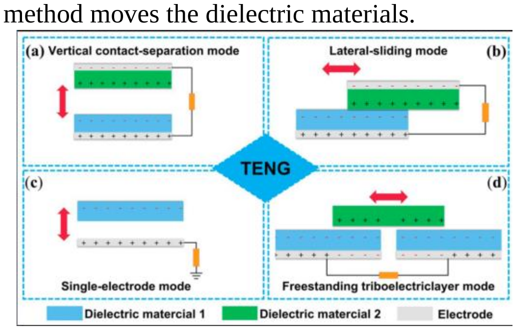

Figure 1 [13]
Triboelectric Nanogenerator Modes

Vertical contact separation mode works by attaching two dielectric materials, or insulators, with different polarities to the back of a current collector [13]. When mechanical force is applied to the materials to make them meet, it makes an electrical charge difference between each of them. After the materials are separated, a potential difference arises between them, which creates a current and transfers the mechanical energy from physical movement into electrical energy. Adjusting the distance between the materials can alter the electrical potential, or voltage, level. This contact separation mode repeats so that a constant alternating current can be produced by the nanogenerator [12].

Lateral sliding mode works similarly to vertical contact separation mode, but instead of using vertical movement, the two dielectric materials are moved horizontally and slide against each other. This sliding increases the lateral polarization, meaning the charges on the two materials are aligned and separated, resulting in the generation of electrical energy in the form of alternating current [13].

In single-electrode mode, the bottom material which behaves as an electrode is grounded, meaning it has an electric potential of zero. The electric field is altered by the above-charged object, so the charge exchange occurs between the electrode and the earth that it's grounded to, and an electric field is generated. The motion for this mode can either be from vertical contact or horizontal sliding [13].

Freestanding triboelectric layer mode involves a pair of symmetrical electrodes beneath a dielectric layer that moves between them. There is a gap between the electrodes, that is the size of the dielectric material [13]. As this dielectric material moves between the electrodes, it generates electric charges and moves them between the electrodes. This flow of charges results in the generation of a current. Because this mode does not require a fixed electrode, it is more adaptable to diverse mechanical energy harvesting situations [13].

The charge-trapping layer helps to maintain the charges and potential difference, or voltage, generated. The surface charges created in the charge-generating layer can combine with the induced opposite charges on the counter electrode [12]. This combination leads to a significant decline in the triboelectric potential as it interferes with the accumulation of charges on the surface. This layer of the TENG typically utilizes materials that have physical defects or specific structures, like certain functional groups that can aid in charge trapping [12].

The charge-collecting layer is meant to collect and transport the charges to an electrode or external circuit, allowing the trapped charges to flow to an external circuit or device which the TENG is attached to. This layer is typically made of conductive materials allowing for the free movement of the charges, such as metals. The charge-collecting layer is positioned to be in contact with the triboelectric material so that the charger can be effectively transferred [12].

The last piece of the TENG is the charge-storage layer. This piece is not always included in triboelectric nanogenerators; however, its purpose is to temporarily store the charges generated by the triboelectric effect before they are used to power an external device [12]. It helps to provide a continuous flow of electricity to the external circuit. The charge-storage layer is considered to be the dielectric material used because these materials can help to maintain the voltage [12].

Improving TENGs

TENGs are not perfect and need significantly more research to make them optimal. In large-scale applications, some of the issues with TENGs include low energy output and lack of durability. The largest issue that is faced by TENGs is the inability to produce large amounts of energy. Many experimental strategies to improve the output performance of TENGs are done through material optimization. Material optimization involves employing friction-generated heat, extending the stability of materials, and managing charge density. As noted by Xu et al., heat generated by friction can reduce the output performance of TENGs [2]. Sohn et al. provides an example of making use of the heat generated from friction. They used "a material of polyurethane with a shape memory effect" as the triboelectric layer [2]. This material can utilize the heat for the glass transition of the material [2]. Glass transition is the transformation of a material from a hard, brittle state to a rubbery state as temperature increases [2]. Because the material has different properties after undergoing glass transition, the material can have stronger triboelectric effects and improved contact electrification. The shape memory property was shown to improve the power generation of the TENG by 300% [2].

An additional example of experimental material optimization is through incorporating functional groups into the surface of the triboelectric materials. Functional groups are parts of molecules that determine the characteristics of the entire molecule. Functional groups with strong electronegativity, or the ability to pull electrons from other molecules, tend to create a negative charge in triboelectricity and those with weak electronegativity typically result in a positive charge. In a specific example, Wang et al. were able to increase the power output of a TENG by four times after modifying the conducting materials with a positive triboelectric functional group, or a weakly electronegative group, and modifying the insulating materials with a negative triboelectric functional group. This result was due to there being a larger difference in charge between the two surfaces [2].

To address the issue of a lack of durability, researchers have come up with many solutions such as fluid lubrication. Due to the wear on the TENG and the build-up of a polymer transfer film, the electrical output decreases. Fluid lubrication was introduced to improve the life cycle of TENGs. The use of liquid lubrication helps to prevent the formation of films on the surface of TENGs and can increase contact area [2]. This allows for increased electrical output and resistance to wear. The voltage and current of a lubricated material have shown to be more than three times that of non-lubricated materials in TENGs and can complete a high number of cycles, about 36,000, without significant wear [2].

TENG WOVEN INTO OUR SOLES: TENG TEXTILES WITHIN SHOES

While TENG is highly versatile, its most common use is in textiles due to its traits, such as its biocompatibility, small size, and high power output. Therefore, TENG technology can be more easily intertwined with fabrics and textiles. When embedded into fabrics and textiles, the small size of the technology allows friction to still occur.

According to author Torah, electronic components such as power storage systems and transducers can be embedded into fibers, which can then be woven into textiles [14]. As explained in "Fiber/Yarn-Based Triboelectric Nanogenerators (TENGs): Fabrication Strategy, Structure, and Application.", there are two main ways the TENG can be incorporated into textiles. The first way is electrospinning, which integrates triboelectric materials on conductive fabrics. Electrospinning is when an electric field draws out liquid polymers to create fragile fibers, usually on the nanometer scale. While this is most common, it still has inevitable downfalls; for example, by doing so, the fabric can become stiffer and bulkier, making the textile itself harder to use [15]. The second method is to incorporate the TENG technology into the fabrics and then use these fabrics to create wearable textiles. The main downfall of this method is that it is more time- and energy-consuming, but it allows the fabrics to be more versatile in their use [15].

These textiles can then be incorporated into wearable garments. Shoes are a highlight because of their direct contact with our body and ground during mechanical movements. According to “Triboelectric nanogenerator built inside shoe insole for harvesting walking energy.”, direct contact causes an increase in friction between the materials, which helps convert mechanical to electrical energy [16]. Collecting mechanical energy through TENG textiles is best seen incorporated in shoes and is one of the most common and efficient uses of TENG technology for energy harvesting. It is seen as more familiar and efficient because of the increased input of mechanical energy we create through everyday movements. Therefore, more energy can be converted into electrical energy. This energy, when converted, can then be used to power or even replace batteries in specific devices, such as global positioning tracking systems and Li-ion batteries.

TENG Textiles Explained

As stated above, TENG technology is mainly incorporated into textiles in two ways. The first way is by integrating triboelectric materials on conductive fabrics; the second is by combining the TENG technology straight into the fabrics.

A primary concern with the TENG technology and textiles was whether the textile could keep its flexibility after being combined with the technology. To address that concern, Wang et al. created a shape-adaptive nanogenerator that contained a conductive liquid in a polymer shell [17]. This innovation helps the device maintain high performance even after being stretched up to 300%. This lets it be woven into bracelets, clothing, or any textile-based product to collect the mechanical energy of the human body. This also does not impact its efficiency, as experiments have shown that the energy collected by the woven materials can light up more than 80 light-emitting diodes. According to “A highly shape-adaptive, stretchable design based on conductive liquid for energy harvesting and self-powered biomechanical monitoring”, through a continuous tapping motion of the wrist, a TENG bracelet was able to 9 volts of energy in 25 seconds [18].

The general fabrication process allows textiles and technology to be efficiently combined to produce the best output. As described in “Triboelectric nanogenerator built inside shoe insole for harvesting walking energy.”, the fabrication involves making a flexible device with patterned polydimethylsiloxane (PDMS) layers and electrodes for energy harvesting [16]. Different materials allow for the triboelectric effect. If there is one positive and one harmful material, a charge will be created, and the material can be harvested. In “Triboelectric Nanogenerators – A Review.”, author Mohan explained how some examples of positive charges include air, skin, leather, nylon, fur, and aluminum. In contrast, some harmful materials include silicon rubber, Teflon, polyvinyl chloride (PVC), polyester—brass, and copper [19]. Figure 2 shows the process in which TENG textiles can both generate and capture the electrical charges.

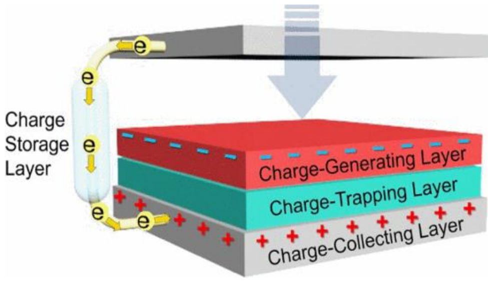

FIGURE 2 [19]
Process of TENG Capturing Energy

The Details of TENG Textiles in Shoes

While TENG textiles have promising futures in many avenues, TENG textiles in shoes have seen much progress since its creation. According to "Self-Powered Versatile Shoes Based on Hybrid Nanogenerators.", in shoes, the TENG textiles work through contact separation, so as someone walks in the shoes, the materials separate and help trap and convert the mechanical energy from walking. The nanogenerators generally act as energy cells in shoes [3]. When the TENG textiles are placed and used in shoe soles, the technology acts as a sensor and can record the acceleration and frequency of people's motions, which are then converted into energy [19]. Figure 3 shows how the TENG textile is used as an energy cell and inserted into a shoe sole to capture mechanical energy from walking.

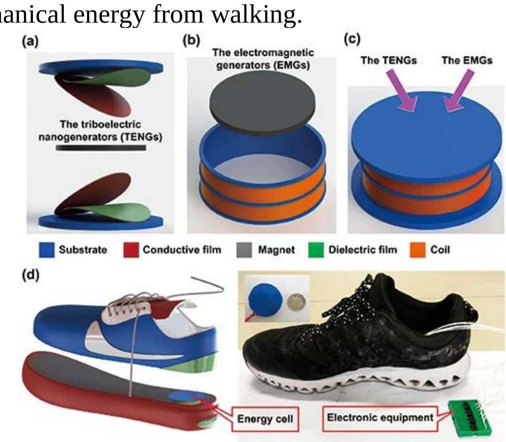

FIGURE 3 [27]
TENG Textiles Incorporated in Shoe Soles

The motion of walking helps separate the two materials in the shoe sole to keep the materials continuously in contact and separated. As explained in "Self-Powered Versatile Shoes Based on Hybrid Nanogenerators.", this continuous contact and separation allow electrons to flow back and forth between "two conductive fabric electrodes due to electrostatic induction," which helps make the electric signals in the external circuit [3]. The mechanical energy, transposed into electrical signals, is then collected in the shoe as it becomes converted into electrical energy stored in its electrical equipment. According to research explained in the article "Triboelectric Nanogenerator: Structure, Mechanism, and Applications", the optimal amount of energy created by the mechanical energy conversion through TENG has been recorded to be 80.3 volts [4]. The energy collection has been optimized with the help of the flexibility of the TENG textiles used in the shoes and the conductive fabric, which ensures electrode elasticity.

Conclusion of TENG Textiles Examples and Applications

The energy generated through TENG textiles, specifically in shoes, has the potential to change how people collect and convert energy for various applications as stated previously. Due to the increased efficiency in capturing mechanical energy, the potential to improve wearable devices' functionality and sustainability increases, too. One of the significant advantages of TENG textile energy harvesting is that the energy created can power and replace the batteries in many low-powered devices. Overall, integrating TENG technology in textiles and specifically into shoes showcases a promising avenue for advancing the field of sustainable energy and technology.

SELF-SUSTAINING ENERGY IN PRACTICAL APPLICATIONS: THE PROS AND CONS

TENG, as stated previously, aids in self-sustaining energy production, and can be used in a variety of different applications, specifically shoe insoles. The research article, "Sustainable Energy Harvesting through Triboelectric Nanogenerators," states that traditional electromagnetic generators compete against TENG for high power output and a variety of large-scale applications such as power grids, construction, and agriculture. What these two have in common is that the generator used can power the machinery used for each application, showing that electromagnetic generators can produce large amounts of power. [20]. However, TENG can be used in a wider variety of small-scale applications with low maintenance at a more sustainable level, compared to the traditional electromagnetic generator. As the article explains, despite the lack of energy output on a large scale TENG is best suited for small-scale applications due to its flexibility, high power output in smaller devices, and ability to be made from renewable or nonrenewable sources [20].

Electromagnetic Generators Compared to TENG

As Q. Xu and L. Tam explain in the Science Direct research article, "Electromagnetic Generator," electromagnetic generators are a device that converts mechanical energy into electrical energy using electromagnetic induction. These types of generators as stated before are seen in everyday life, but can also be used in power plants, portable generators, wind turbines, and hydroelectric dams. Similar to TENG, both generators convert mechanical energy to electrical energy. However, TENG works through friction. While electromagnetic generators are designed for wide-scale applications, TENG specializes in the nanoscale, making them useful for small-scale power generation [6]. These small-scale applications can be best seen in wearable electronics, wind energy, and water energy.

Nanoscale TENG Application Benefits

As D. Barkas, C. Psomopoulas, et.al, explain in the article "Sustainable Energy Harvesting through Triboelectric Nanogenerators," that TENG in small-scale applications offers several advantages including small size, lightweight, flexibility, and ability to harvest energy from various mechanical motions in the environment [5]. From the research article, "Size effect on the output of a miniaturized triboelectric nanogenerator based on superimposed electrode layers," written by Q. Wand, M. Chen, et.al TENG layers can be as small as 2 cm x 2 cm as seen in figure 4,[21].

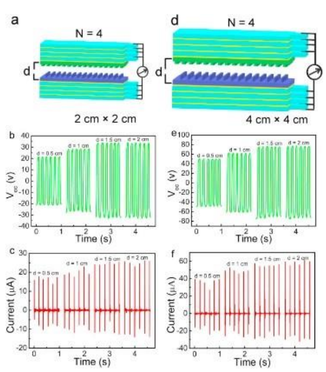

Figure 4 [21]

Size of Triboelectric Nanogenerators

In addition to their small size, TENG layers can be lightweight and flexible, for example, Z. Li, H. Li, et al, write in their research article, "Small-Sized, Lightweight, and Flexible Triboelectric Nanogenerator Enhanced by PTFE/PDMS Nanocomposite Electret," TENG as a wearable electronic device, has a thickness of 1.3 mm and a weight of 1.7 grams. Due to its lighter weight, TENG can be attached to the human body with no issues allowing for harvesting mechanical energy to be flexible for many environments. [7].

TENG Beyond Wearable Electronics

The Power of Wind

The ability of TENG to harvest energy from mechanical motions with its lightweight and flexible capabilities shows TENGs adaptability to its environment. TENG can harvest energy from human movements, but also from wind and ocean waves. In the research paper, "Strategies for effectively harvesting wind energy based on triboelectric nanogenerators," Z. Ren, L. Wu, et al, write that "for current wind energy harvesting, the wind turbine based on electromagnetic effect has been the most widely used approach. However, the wind turbine is not very effective for harvesting low-speed wind sources…" [22]. The paper then introduces the idea that by moving from the electromagnetic effect to the TENG technology, wind energy can be sourced by using nano-manufacturing technologies instead of large turbines. By using TENG for this type of energy harvesting, devices can be made as small as 2.5 cm x 2.5 cm x 22 cm, significantly decreasing the materials used to make the turbines [23]. When wind is applied to this TENG device, there is enough energy to light tens of LEDs. "With this structure, the collection of wind sources with arbitrary directions in the surrounding environment can be realized, even under severe weather conditions" [22]. With the power of wind energy, TENG can be used in large-scale applications at a nano-scale.

TENG In Ocean Waves

TENG can be seen harvesting energy from clothes, in the wind, and even in ocean waves. In the research paper, "Emerging triboelectric nanogenerators for ocean wave energy harvesting:

state of the art and future perspectives," C. Rodrigues, D. Nunes, et al, explain that efficient, low-cost, and environmentally friendly maritime technologies to harvest wave energy are limited [23]. The irregular nature of ocean waves makes using electromagnetic generators difficult to use. TENG, however, can convert irregular "oscillatory," as C. Rodrigues, D. Nunes, et al write, energy into electricity despite any slow motions of waves [23]. When comparing TENG's lightweight and flexible applications, wave energy does not lack as the research paper explains, "The technology itself is also lightweight and has inherent low fabrication costs, giving it an important potential edge over alternative systems for wave energy conversion, as cost reduction is a vital challenge that needs to be addressed by the wave energy sector"[23]. In figure 5, it can be seen that TENG is installed in a hull, or a watercraft, so that the swaying and rolling motions of a wave can excite the triboelectric effect, resulting in harvesting wave energy [23]. Additionally, in figure 6, TENG is designed in a tower with cylindrical 15 x 7cm^2 shells. This type of TENG device can generate a voltage of 250 V with an average power density of 13.2 mWm^-2 per wave movement [23]. TENG in wind or wave power on top of human motion harvested power supports TENG's versatility where conventional power sources are unavailable or impractical.

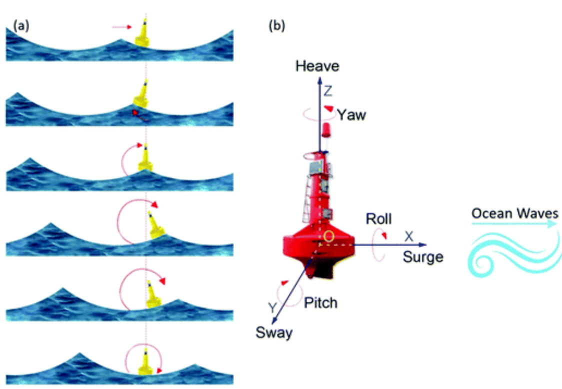

Figure 5 [23]

TENG in a Hull

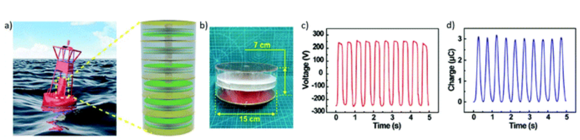

Figure 6 [23]

TENG Cylindrical Tower

Drawbacks of Nano-Scale Energy Harvesting

TENG demonstrates that energy can be harvested in small-scale devices for larger applications, nonetheless, there are notable disadvantages. Compared to traditional energy sources like batteries or grid power, TENGs have generally lower power densities. According to the article, "The Effect Energy Density Has On the Power of Your Battery," an average lithium-ion battery has about 150-200 watt-hours per kilogram [24] Then, from the Environmental and Energy Study Institute, "Fact Sheet," a large-scale battery storage energy grid, 708 milli-watts can be generated [25]. Such large numbers make TENG's power density output of a respective 42 milli-watts from the article, "Output power density enhancement of triboelectric nanogenerators via ferroelectric polymer composite interfacial layers," in its small-scale applications appear much smaller compared to the previous examples. [26].

While these disadvantages exist, ongoing research and development efforts are addressing many of these challenges. Such as aiming to enhance the performance, reliability, and applicability of triboelectric nanogenerators in various fields and applications stated previously in wind, waves, and clothes.

SUSTAINABILITY BUILT INTO TENG

Evaluating the sustainability of TENG requires addressing multiple factors, namely the materials used to make the TENG application. Using natural materials in TENG devices shows biodegradability, promoting sustainable technology. However, challenges remain in achieving optimal sustainability due to lower power outputs compared to synthetic materials. This leads to continued reliance on precious metals in industrial applications despite their environmental costs. With more research, TENGs sustainability efforts can grow by leveraging natural materials in small-scale applications.

Positive TENG Sustainability Efforts

Having the ability to generate and harvest electricity gives TENG the lead in sustainable energy use in small-scale demand. The research paper, "Environmentally Friendly Natural Materials for Triboelectric Nanogenerators: A Review," by L. Liu, et al, explain Biodegradable, natural materials such as animals, plants, and microorganisms can be placed into the friction layer in TENG without drastic changes in output voltage power [8]. By utilizing natural materials for the main friction layer in TENG, precious metal mining can be stopped. This allows for the environmental hazards of TENG to be limited [8].

Natural Materials Used in TENG

The natural materials that can be used in TENG are derived from a variety of ecosystems, notably, animal parts, plants, the human body, and microorganisms. L. Liu, et al, explains that from animal materials, pigeon feathers, and rabbit fur are good at exhibiting durability in the friction layers. Pigeon feathers are a strong, durable natural material that can withstand hard environments such as wind and rain [8]. The paper also explains that fish scales and crab shells as biowaste are biodegradable. Due to the gelatin in fish scales, the electron-donating amino grounds can easily transfer electrons during friction. Thus, making the transition from tribo-positive and tribo-negative layers possible. As seen in Figure 7, the TENG-based fish scales can be used in powering LEDs and LCDs because of their thinness and flexibility [8]

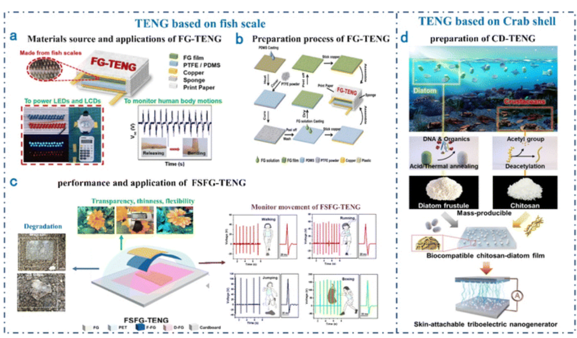

Figure 7 [8]
TENG Based on Fish Scales

In plants, vegetable leaves such as leeks can be used in the triboelectric layer in TENG devices. L. Liu, et al, state that by using leek skins in TENG devices with an open circuit there was a 182 V output, lighting 48 LEDs and charging a 0.47 µF capacitor to 8.91 V [8]. The rough texture of the leek skins allows for extensive friction to be produced when rubbed together for triboelectric harvesting. In addition to leaves, cotton has a high output performance due to its OH, hydroxide, making it a good tribo-positive material. The roughness of cotton increases when fluoride is added, increasing the friction and negative charge on its surface. The modified cotton TENG can then give an output voltage of 216.82 volts and a current of 50.33 µA, microampere, with unmodified cotton the voltage output equates to 39.23 V and 0.2 µA. Figure 8 from the article by L. Liu, et al, show the difference between TENG-based natural cotton and modified cotton comparing the roughness [8]. This type of TENG material was operated for 14 days to monitor voltage and current, and at the end of observation, the cotton TENG showed stability and durability.

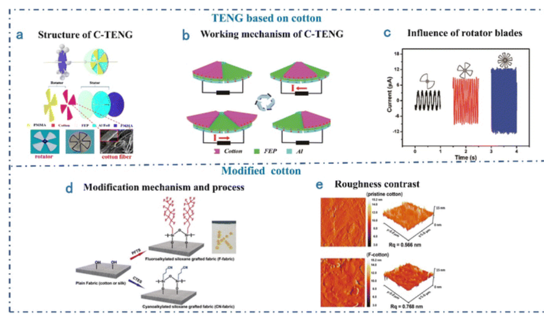

Figure 8 [8]
TENG Based Cotton

Similar to plants and animal materials, the human body can be used in TENG. In L. Liu, et al's, research paper, they explain that human skin naturally is unable to decompose metal electrodes on triboelectric materials, but when using single-electrode-based TENG energy harvesting is possible. Skin can be used as a friction layer, specifically using a finger, the skin then is created into a tribo-positive layer. By using the skin on the tip of a finger in a TENG device, power output voltages can be as high as 66 volts. [8]. Figure 9 shows how TENG can be seen in section A from finger contact, and in section B as energy harvesting on the human body. This example in section B shows energy being generated from the movement of a human wearing a shoe coming into contact with the ground and then being able to use this harvested energy to light an LED [8]. This directly relates to TENG being used in the textile industry as shoe insoles. From the research done by L. Liu, et al, the voltage output equated to 400 volts with a current of 12 µA from using the contact of the rubber of a shoe and the ground from walking [8]. The impact from the movement of the human body creates charges, and TENG is then able to harvest this energy.

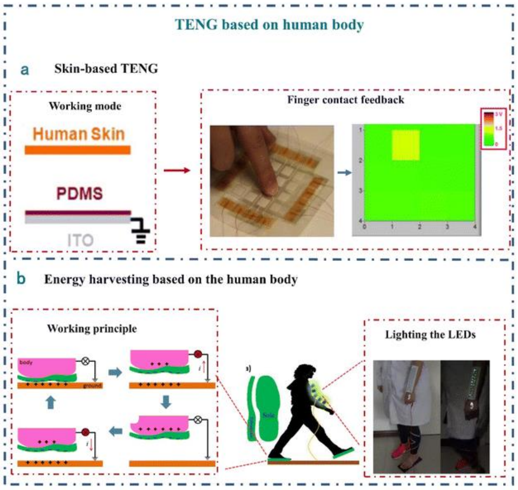

Figure 9 [8]
TENG Based on Human Body

Lastly, microorganisms can be used as materials in TENG friction layers as well. Bacteria in TENG promote flexibility and compatibility. For example, L. Liu, et al., write, "Bacterial cellulose (BC) can be extracted from bacteria and has a unique 3D porous network and crystalline nanofibers with a diameter of 10–100 nm.160,161 [HT9] BC has high purity, crystallinity, porosity, liquid and gas permeability, good biocompatibility, and mechanical stability. Moreover, BC is an environmentally friendly natural material that can be completely decomposed within 30 days" [8].

BC, bacterial cellulose, in TENG is based on bacterial nanocellulose, BCN, in the tribo-negative layer and shows characteristics of flexibility and biocompatibility similarly. When using the BCN-TENG film 13 volts is able to be collected, moreover, BC-TENG as a friction layer was able to reach output voltages of 29 volts with currents of 0.6 µA [8]. In addition to these numbers, BC-based TENGs could be used to successfully transmit signals and play music when connected to a microcontroller. As stated previously, BC-TENGS, from being a bacterium, is extremely productive at biodegrading and can degrade within 8 hours [8]. Further, bacteria is extremely productive when implemented with TENG due to its unique characteristics and ability to produce an output voltage.

Negative TENG Sustainable Implications

Though TENG was evaluated as a sustainable mode of energy harvesting, the ability of such technology to be used to its full sustainable potential is difficult to achieve. The reason for this is that using TENG with natural materials is still being researched. As C. Dagdeviren, et al, explain in "Energy Harvesting from the Animal/Human Body for Self-Powered Electronics," the main challenge of using natural material-based TENGs is the lack of natural tribo-negative materials, meaning that PDMS and PET materials are still best at having high output voltage at a readily available time [27]. Additionally, the life span of these materials is short due to their rapid aging and decomposition. Plant materials also lose friction due to surface texture fading and drying. Lastly, in terms of natural material TENG, the power output of these TENGs is generally low [8]. When using synthetic materials, the output power can reach tens of thousands of milliwatts, whereas natural materials reach tens to hundreds of milliwatts. The full sustainable potential of TENG is hindered by challenges in utilizing natural materials, resulting in lower power output compared to synthetic counterparts.

Consequently, because natural-based TENG is best suited for textile use, industrial small-scale TENG use still utilizes precious metals such as copper and aluminum. The mining of these materials is not sustainability sourced.

Aluminum mining, processing, and refining is energy intensive. From The Aluminum Association's article, "Bauxite 101," aluminum is primarily mined in Australia, China, Brazil, India, and Guinea, where tens of millions of metric tons of bauxite, the most common ore of aluminum, is mined. To mine bauxite, there are a series of steps starting with drilling, then blasting, crushing, and grinding the environment around to extract the ore. Once extracted bauxite is refined to remove impurities [2]. This whole process according to the article, "Aluminum Production - An Overview," about 17,000 kWh of electricity are required to produce 1 tonne of aluminum. In comparison, the energy to power a house takes about 30 kWh of electricity [29]. Such mining leads to rainforest destruction, toxic waste leakages into rivers making as Rainforest Rescue defines, "dead zones," and degradation of air quality from dust pollution [30]. From the National Institute of Health's article, "Potential Health Impacts of Bauxite Mining in Kuantan," to mine the bauxite ore, open mining involves clearing and removal of land, resulting in the removal of topsoil and vegetation. This mining causes toxic waste to pollute the air of nearby communities as seen in figure 10 [9] In figure 10, the excavation of bauxite using open mining caused the nearby school area to close. Because the mining site is close to the school, in figure 11, dust pollution can be seen covering the school floor. When inhaled, dust can travel into the respiratory system increasing the risk of asthma, respiratory problems, cardiovascular problems, and irritation to eyes, throat, and skin [9].

Figure 10 [9]
School Mining Site

Figure 11 [9]
School Floor With Dust

Copper mining also has severe impacts on the environment and drinking water posing risks to public health. From the University of Arizona's article, "Copper Mining and Processing: Processing Copper Ores," the process of mining copper is usually performed using open-pit mining, where holes are dug deep into the ground. Once dug, to remove the ore more drilling is done to separate the rock from the hard dirt, and then explosives are used to blast and expose the ore [31]. The USGS's article, "How much copper has been found in the world?" much of the copper taken from the ground has been found in only five countries, Chile, Australia, Peru, Mexico, and the United States [3]. Like aluminum, copper is a finite source and in 2022 the world collectively mined 22 million tons of copper, according to Government of Canada [33].

Additionally, regulation of copper mining is not heavily controlled leading to contaminated water and decreasing water safety. According to the article, U.S. Copper Porphyry Mines," from Earthworks, the main sources of copper pollution are pipeline spills, tailing failures, and water collection/treatment failures [34]. The quote from this article demonstrates how copper mining has affected water quality, "Our research shows that water quality impacts to surface and/or groundwater are common at currently operating copper porphyry mines in the U.S., resulting from three failure modes (pipeline spills or other accidental releases, failure to capture and treat mine seepage, and tailings spills or impoundment failures)." [34]. In figure 12 from the article by R. Garwin, "How Sulfide-Ore Copper Mines Pollute,", the orange-tinted water is a result of copper pollution [35]. Because copper mines are located near waterways, copper toxins often leak into drinking water aquifers. Thus, contaminating farmland, releasing toxins into fish and neighboring wildlife, and the public [34].

Figure 12 [35]
Copper Waste into Waterways

The aluminum and copper mining industry poses major environmental hazards, and when these metals are used in TENG, the sustainability of TENG decreases. However, with more experimentation and research, natural material based TENG can be further implemented into more TENG applications, beyond textiles.

TENG Can Be Sustainable with the Proper Approach

The materials to make this technology can be sustainably sourced, from biodegradable materials, or industrially mined. When making TENG with natural materials it can be biodegradable, biocompatible, and contain similar triboelectric effects to when using precious metals. These natural materials though do not produce as high an output voltage score as when using precious and synthetic materials. By using these precious metals, the output voltage is significantly higher, but at the cost of environmental destruction from mining and polluting waterways and ecosystems with unregulated clean-up efforts. Nevertheless, the downsides of TENG such as the low power output and mining of precious metals can be quickly diminished when using TENG in small-scale applications using natural materials and textiles.

WEAVING IT ALL TOGETHER

Triboelectric Nanogenerators (TENGs) offer a promising solution to address the challenge of providing more people with access to sustainable electricity. These devices harness mechanical energy from everyday activities to generate electric power. The utilization of TENGs aligns with the growing demand for sustainable energy sources.

Within textiles, TENGs embedded in shoe insoles exemplify a practical application of this technology. Through continuous use, the mechanical energy generated during human movement can be converted into usable electrical power. TENG technology has great potential for acting as a sustainable and easily accessible power source for portable electronic devices.

While TENG shoe insoles are effective, the application of TENGs in textiles extends beyond shoe insoles, with possibilities ranging from clothing to accessories. Imagine garments capable of harvesting energy from body movements, or backpacks equipped with TENGs to capture energy during walking or hiking. This broader integration of TENG technology into various aspects of daily life showcases its versatility and potential to contribute to sustainable energy solutions.

As we explore innovative ways to address energy needs across the world, TENGs emerge as a key player in sustainable power sources. Their ability to convert mechanical energy from everyday activities into electricity not only offers a practical and sustainable solution but also aligns with the increasing focus on renewable and eco-friendly technologies. TENGs represent a step towards making energy harvesting an integral part of our daily lives, transforming the way we think about and utilize power.

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WRITERS' NOTE

We took your comments on the paper into consideration and tried to focus on introducing our sources. Based on your comments we made sure to add introductions to all our sources. We also made sure to proofread our paper. We specifically looked into our syntax and repetition and tried to make sure all sections of the paper were consistent with each other. We made sure to add more details on how the TENGs create and store electrical energy from movements, and overall worked on increasing our specificity throughout the paper.

FYEC Team/Paper number (for example, FYEC Team12)
0412 Professor (for example, Professor Janine Carlock)

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Overall Comment:

Grade:

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What's Working Well		What Could Be Improved
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